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Diffuse Galactic gamma rays, cosmic-ray nucleons and antiprotons

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Abstract. The excess of continuum γ-ray emission from the Galaxy above 1 GeV is an unsolved puzzle. It may indicate that the interstellar nucleon or electron spectra are harder than local direct measurements, as could be the case if a local source of cosmic rays were to dominate the nearby flux. It is however difficult to distinguish between the two cases. Cosmic-ray secondary antiprotons provide a way to resolve this issue.

We have made a calculation of the cosmic-ray secondary antiproton spectrum in our model, which computes self-consistently propagation of primary and secondary nucleons, and electrons. Fragmentation and energy losses are computed using realistic distributions for the interstellar gas and radiation fields, and diffusive reacceleration is also incorporated. Our study shows that accurate measurements of the antiproton flux, especially at high energies, could provide a diagnostic of the interstellar nucleon spectrum allowing us to test the hard nucleon spectrum hypothesis. Present antiproton data above 3 GeV indicate that it can already be excluded at the few σ level.

Key words: diffusion – elementary particles – cosmic rays – ISM: general – Galaxy: general – gamma rays: theory

1. Introduction

The spectrum of Galactic γ-rays as measured by EGRET shows enhanced emission above 1 GeV in comparison with calculations based on locally measured proton and electron spectra assuming the same spectral shape over the whole Galaxy (Hunter et al. 1997; Gralewicz et al. 1997; Mori 1997; SM97; MS98a). The γ-ray observations therefore indicate that their spectra on the large scale in the Galaxy could be different. Harder cosmic-ray (CR) spectra could provide better agreement, but the γ-ray data alone cannot discriminate between the π^0-decay and inverse Compton explanations (MS98b). Although the hard electron spectrum hypothesis seems to be more likely due to the probably clumpy distribution of electrons at high energies (e.g., Pohl & Esposito 1998), the hard nucleon spectrum cannot be ruled out. Explicitly, we consider the case that the local nucleon spectrum is not representative of the regions within a few kpc of the sun, as could occur if a nearby source of cosmic rays dominates the observed fluxes.

An important clue may be provided by secondary antiprotons in Galactic CR produced in collisions of CR particles with interstellar matter[1]. These are an important diagnostic for models of CR propagation and provide information complementary to that provided by secondary nuclei such as Be, B, and heavier nuclei. However, unlike secondary nuclei, antiprotons reflect primarily the propagation history of the protons, the main CR component. The observed intensities depend on the spectrum of CRs, their composition, details of the nuclear cross sections, and propagation in the Galaxy. Because they are secondary, antiprotons reflect the large-scale nucleon spectrum independent of local irregularities in the primaries.

Previous calculations of secondary $\bar{p}$'s have been made on the basis of the leaky box model (e.g., Gaisser & Schaefer 1992; Simon & Heinbach 1996) and the locally observed nucleon spectrum. Recently several experiments have provided improved data on both the $\bar{p}/p$ ratio and the $\bar{p}$ spectrum itself (Hof et al. 1996; Mitchell et al. 1996; Boezio et al. 1997; Moiseev et al. 1997), and the latest calculations by Simon et al. (1998) indicate good agreement with the data.

We have developed a propagation code which aims to reproduce self-consistently observational data of many kinds related to CR origin and propagation: direct measurements of nuclei, electrons and positrons, γ-rays, and synchrotron radiation. These data provide many independent constraints on any model and our approach is able to take advantage of this since it must be consistent with all types of observation (Strong 1996; SM97; MS98a). In this paper we present results on the evaluation of the $\bar{p}$ spectrum and $\bar{p}/p$ ratio in a model including diffusion and reacceleration and different nucleon injection spectra. Our aim is to show that $\bar{p}$'s provide a critical test of the alternative explanations of the GeV γ-ray excess. Other secondaries, such as positrons, also provide a test (MS98b), but are more affected by energy losses. In MS98a we considered the positron fraction as evidence favouring a hard nucleon spectrum, but

[1] Secondary origin of CR antiprotons is basically accepted, though some other exotic contributors such as, e.g., neutralino annihilation (Bottino et al. 1998) are also discussed.

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the spectrum considered was not as hard as required to reproduce the γ-ray data, and also absolute positron fluxes were not available at that time. In MS98b we show that positron results indeed confirm the conclusion of the present paper.

2. Description of the models

The models are three dimensional with cylindrical symmetry in the Galaxy, and the basic coordinates are (R, z, p), where R is Galactocentric radius, z is the distance from the Galactic plane, and p is the total particle momentum. The propagation region is bounded by ($R_{\rm h}$, $\pm z_{\rm h}$) beyond which free escape is assumed. We take $R_{\rm h} = 30$ kpc, $z_{\rm h} = 4$ kpc since this is consistent with our B/C and ^{10}Be/^{9}Be study (Strong & Moskalenko 1998a; SM98b). For a given $z_{\rm h}$ the diffusion coefficient as a function of momentum is determined by B/C for the case of no reacceleration; if reacceleration is assumed then the reacceleration strength (related to the Alfvén speed, $v_{\rm A}$) is constrained by the energy-dependence of B/C (Seo & Ptuskin 1994). The spatial diffusion coefficient for the case of no reacceleration is taken as $D_{xx} = \beta D_0(\rho/\rho_0)^{\delta_1}$ below rigidity ρ_0, $\beta D_0(\rho/\rho_0)^{\delta_2}$ above rigidity ρ_0. The spatial diffusion coefficient with reacceleration is $D_{xx} = \beta D_0(\rho/\rho_0)^{\delta}$ with $\delta = \frac{1}{3}$ for all rigidities, and the momentum-space diffusion coefficient D_{pp} is related to D_{xx} (Berezinskii et al. 1990; Seo & Ptuskin 1994). The injection spectrum of nucleons is assumed to be a power law in momentum. The values used are $D_0 = 3.5 \times 10^{28}$ cm^2 s^{-1}, $\rho_0 = 5$ GV, $\delta_1 = -0.60$, and $\delta_2 = +0.60$ for nonreacceleration models, and $D_{xx} = 6 \times 10^{28}$ cm^2 s^{-1} at 3 GV and $v_{\rm A} = 20$ km s^{-1} for reacceleration models.

The interstellar hydrogen distribution uses HI and CO surveys and information on the ionized component; the Helium fraction of the gas is taken as 0.11 by number. Energy losses for electrons and nucleons are included (SM98b). The distribution of CR sources is chosen to reproduce the CR distribution determined by analysis of EGRET γ-ray data (Strong & Mattox 1996). The secondary nucleon source functions are computed from the propagated primary distribution and the gas distribution. The γ-ray emission from π^0-decay, inverse Compton and bremsstrahlung are computed explicitly in 3D from the propagated nucleon and electron spectra.

The calculated B/C ratio is shown in Fig.1 together with recent data, and the agreement indicates that our propagation models are satisfactory. Our preliminary results were presented in SM97 and full results for protons, Helium, positrons, and electrons in MS98a. Evaluation of the B/C and ^{10}Be/^{9}Be ratios, evaluation of diffusion/convection and reacceleration models, and limits on the halo size, as well as full details of the methods are summarized in SM98b. More details are available on the WWW (http://www.gamma.mpe–garching.mpg.de/∼aws/aws.html).

2.1. Antiproton cross sections

We have used a 'standard' formalism to calculate $\bar{p}$ production and absorption in the interstellar medium. Antiproton production in pp-collisions has been calculated using the Tan & Ng (1983a) parametrization of the invariant $\bar{p}$-production cross section. The total $\bar{p}p$ inelastic cross section has been calculated using a fit by Tan & Ng (1983b). The cross section for $\bar{p}$ production in proton-nucleus and nucleus-nucleus interactions has been obtained (following Gaisser & Schaefer 1992) by scaling the pp invariant cross section with a factor $F_{it\to\bar{p}X} = (A_i\sigma_{pt}^{\rm inel} + A_t\sigma_{pi}^{\rm inel})/2\sigma_{pp}^{\rm inel}$, where $A_{i,t}$ are the atomic numbers of the incident and target nuclei. For the cross sections $\sigma_{pp}^{\rm inel}$ and $\sigma_{pA}^{\rm inel}$ we adapted parametrizations by Tan & Ng (1983b) and Letaw et al. (1983), correspondingly. The $\bar{p}$ absorption cross section on an arbitrary nuclear target has been scaled by $A^{2/3}$ using the measured $\bar{p}$–^{12}C cross section (Denisov et al. 1973; Carroll et al. 1979; Nakamura et al. 1984, Kuzichev et al. 1994).

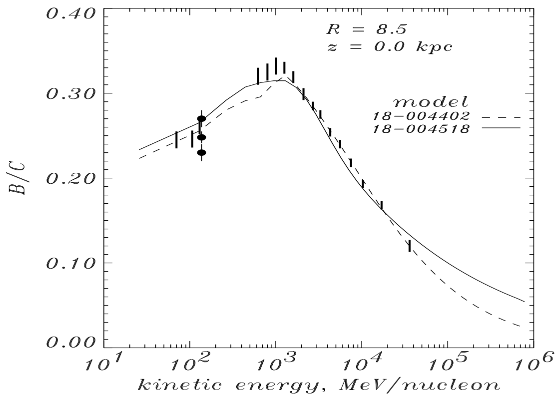

Fig. 1. B/C ratio for the models with (solid) and without reacceleration (dashed), $\Phi = 500$ MV. Data: vertical bars: HEAO-3, Voyager (Webber et al. 1996), filled circles: Ulysses (DuVernois et al. 1996).

Simulations of the $\bar{p}$ production with the Monte Carlo model DTUNUC (Simon et al. 1998), which appear to be more accurate than simple scaling, have shown that He nuclei contribute about 18% to the total $\bar{p}$ yield and their contribution remains a constant above the kinetic energy $T_{\bar{p}} \sim 500$ MeV. Heavier nuclei contribute at about the 3% level. Therefore, even if our simple scaling lowers the $\bar{p}$ yield on nuclei by a factor of 2 (which is unlikely at $T_{\bar{p}} \gtrsim 500$ MeV), then the total yield is not underestimated by more than 10%. In fact, other uncertainties dominate the secondary production, for example the form of the interstellar nucleon spectrum.

Another simplification is that $\bar{p}$'s surviving after an inelastic collision are totally ignored. However, calculations made with only the annihilation cross section show that the difference is small and the effect can be neglected.

3. γ-rays

Fig. 2 (left) shows as an example the γ-ray spectrum of the inner Galaxy for a ('normal') model which matches the directly observed electron and nucleon spectra (the latter is shown in Fig. 4 left). The fit to the EGRET spectra is satisfactory from 30 to 500 MeV and the deficit above 1 GeV is evident, as dis-

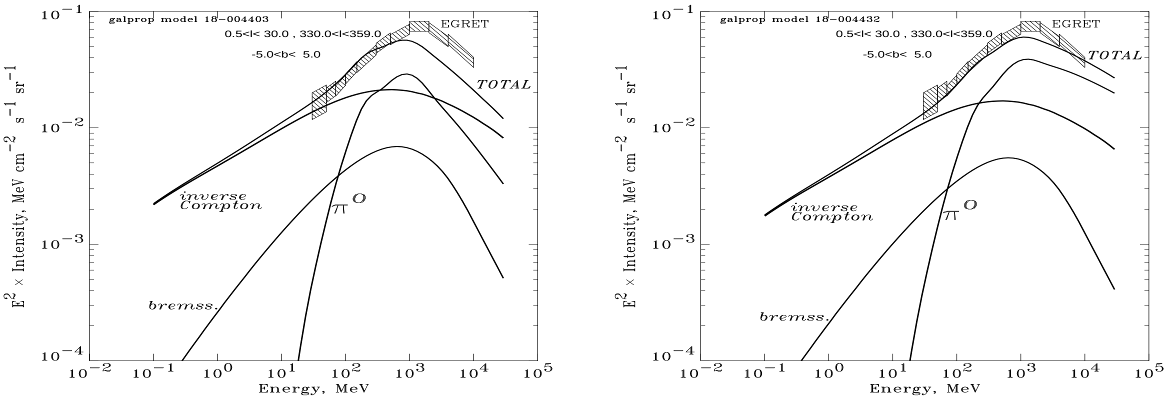

Fig. 2. *Left panel:* Gamma-ray spectrum of inner Galaxy ($330^\circ < l < 30^\circ$, $-5^\circ < b < 5^\circ$) as measured by EGRET (Strong & Mattox 1996) compared to model with 'normal' nucleon and electron spectra. Also shown are the contributions of individual components: bremsstrahlung, inverse Compton, and π^0-decay. *Right panel:* The same compared to the model with the *hard nucleon* spectrum (no reacceleration).

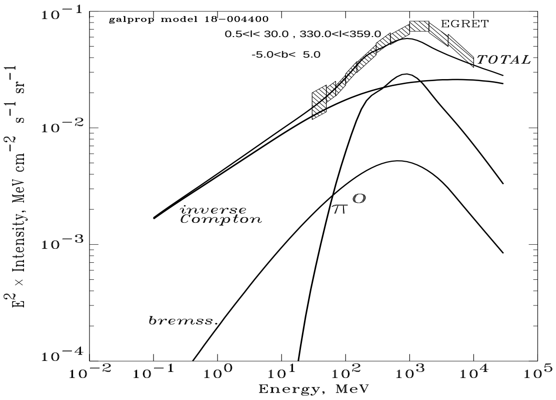

Fig. 3. The EGRET γ-ray spectrum of inner Galaxy compared to model with the *hard electron* spectrum (no reacceleration). Individual components are the same as in Fig. 2.

cussed in the Introduction. Simple rescaling of either electron or nucleon spectra does not allow the agreement to be signficantly improved.

A model with a hard nucleon injection spectrum (no reacceleration, injection index 1.7) is shown in Fig. 2 (right). The corresponding propagated interstellar proton spectrum is shown in Fig. 4. Fig. 3 shows a model with a hard electron injection spectrum (no reacceleration, injection index 2.0). Both models reproduce approximately the observed spectrum, and latitude and longitude profiles, almost equally well (MS98b), and hence it is difficult to discriminate between them.

The same nucleons which contribute to the GeV γ-ray emission through the decay of π^0-mesons also produce secondary $\bar{p}$'s (on the same interstellar matter). The harder nucleon spectrum hypothesis, therefore, can be tested with reliable measurements of CR $\bar{p}$'s. Above $T_p \sim$ few 10 GeV the mean energy of parent protons is about 10 times larger than the kinetic energy of produced $\bar{p}$'s, and roughly the same holds for γ-rays, so 10 GeV $\bar{p}$'s and γ's both are produced by $\approx$100 GeV nucleons. Thus, the test is well tuned.

4. Antiprotons

First we consider the 'normal' case, with nucleon injection spectra which after propagation and modulation match those locally observed (Fig. 4 left). Our calculations of the interstellar $\bar{p}$ spectra and $\bar{p}/p$ ratio for these spectra are shown in Fig. 4. The computed $\bar{p}$ spectrum is divided by the same interstellar proton spectrum, and the ratio is modulated to 750 MV. The corresponding ratios are shown on the right panel. We have performed the same calculations for models with and without reacceleration and the results differ only in details. As seen, our result agrees well with the calculations of Simon et al. (1998), showing that our treatment of the production cross-sections is adequate as discussed in Section 2.1.

We now turn to the case which matches the γ-ray data at the cost of a much harder proton spectrum than observed (Fig. 2 right). The dashed lines in Fig. 4 (right) show the $\bar{p}/p$ ratio for the hard proton spectrum (with and without reacceleration); the ratio is still consistent with the data at low energies but rapidly increases toward higher energies and becomes $\sim$4 times higher at 10 GeV. Up to 3 GeV it does not confict with the data with their very large error bars. It is however larger than the point at 3.7–19 GeV (Hof et al. 1996) by about 5σ. Clearly we cannot conclude definitively on the basis of this one point[2], but it does indicate the sensitivity of this test. In view of the sharply rising ratio in the hard-spectrum scenario it seems unlikely that the data could be fitted in this case even with some re-scaling due to propagation uncertainties. It is interesting to note that the local $\bar{p}/p$ ratio seems to depend only slightly on the details of the propagation.

[2] We do not consider here the older $\bar{p}$ measurement of Golden et al. (1984) because the flight of the early instrument in 1979 was repeated in 1991 (Hof et al. 1996) with significantly improved instrument and analysis techniques. Thus the latter data are more reliable and the relevance of this measurement to the earlier one is indicated in Hof etal.

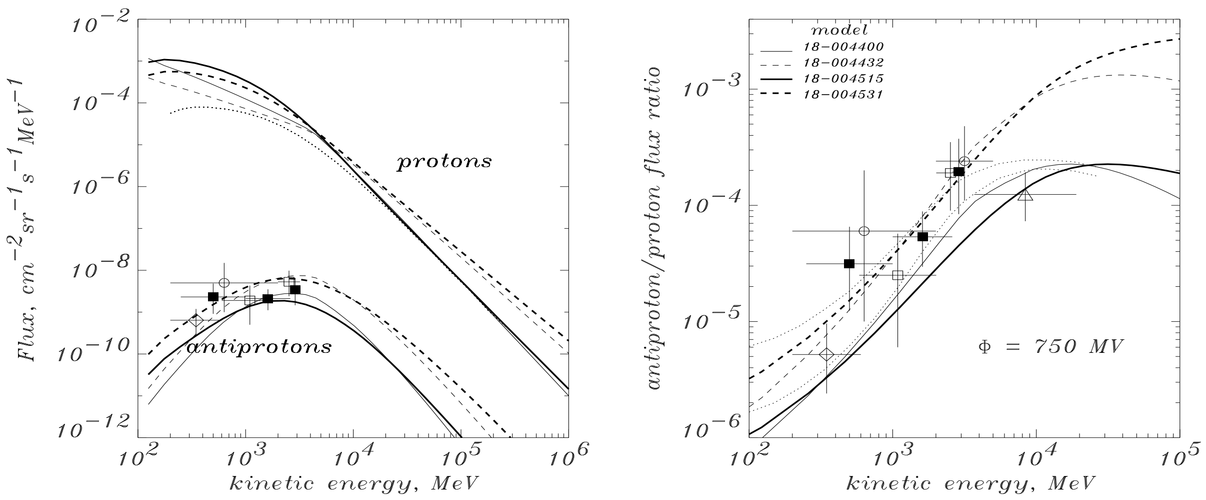

Fig. 4. *Left panel:* Interstellar nucleon and antiproton spectra as calculated in nonreacceleration models (thin lines) and models with reacceleration (thick lines). Spectra consistent with the local one are shown by the solid lines, hard spectra are shown by the dashed lines. The local spectrum as measured by IMAX (Menn et al. 1997) is shown by dots. *Right panel:* $\bar{p}/p$ ratio for different ambient proton spectra. Lines are coded as on the left. The ratio is modulated with $\Phi = 750$ MV. Calculations of Simon et al. (1998) are shown by the dotted lines. Data from: ■ Boezio et al. (1997), ○ Bogomolov et al. (1987,1990), △ Hof et al. (1996), □ Mitchell et al. (1996), ◇ Moiseev et al. (1997).

Our main conclusion is that antiprotons provide a *sensitive test* of the interstellar nucleon spectra and hypotheses for the origin of diffuse Galactic γ-rays. On the basis of the $\bar{p}/p$ data point above 3 GeV we seem already to be able to exclude the hypothesis that the local CR nucleon spectrum differs significantly from the Galactic average (by implication adding support to the 'hard electron' alternative), but confirmation of this conclusion must await more accurate data at high energies. In this respect we note that the $\bar{p}/p$ ratio from Hof et al. (1996) is currently being refined and absolute $\bar{p}$ fluxes will be calculated (Hof 1998, private communication). Additionally, a re-flight of the CAPRICE instrument (Boezio et al. 1997) took place in spring 1998, and several other balloon instruments could be adapted for antiproton measurements (HEAT: Barwick et al. 1997), ISOMAX: Streitmatter et al. 1993). On longer timescale several satellite experiments are planned or under construction (e.g., PAMELA: Adriani et al. 1995; AMS: Ahlen et al. 1994). These new experiments should allow us to set stricter limits on the nucleon spectra including less extreme cases than considered here, and to constrain better the interpretation of γ-rays.

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